AlInP-Based LEDs for Efficient Red and Amber Emission

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Background and Importance

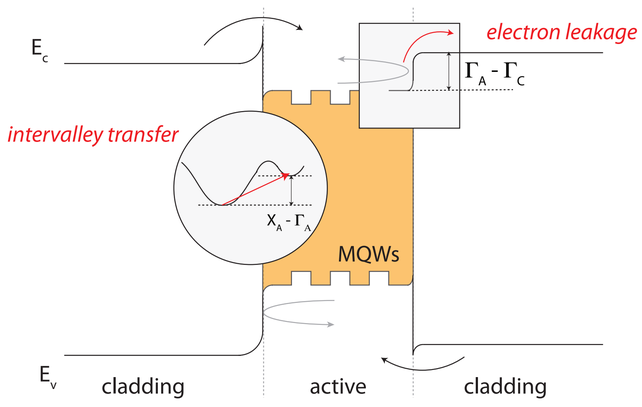
Overview

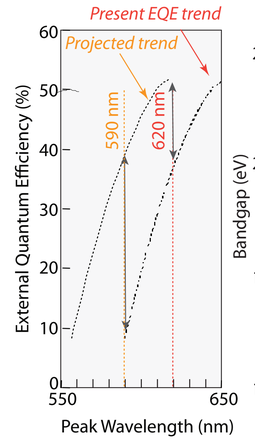
Red and amber phosphide-based LEDs have efficiencies well below blue InGaN LEDs, in part due to fundamental limitations of the materials from which they are made. The efficiencies of these LEDs must be improved to enable next-generation color-mixed white LED architectures.

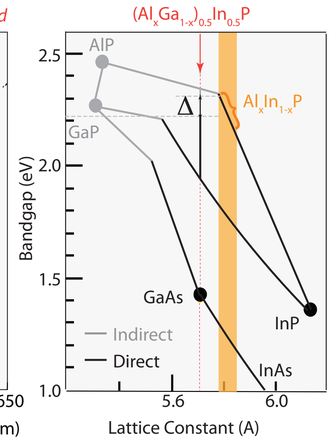
We are addressing the limitations of phosphide-based LEDs by modifying the materials that are used for the active and cladding layers. **The objective of this project** is to demonstrate the feasibility of fabricating red and amber LEDs from ordered/disordered $Al_xIn_{1-x}P$ heterostructures and to quantify the performance improvements this design can yield over incumbent phosphide LEDs.

Color*	Wavelength	Emitter Type	Material	Spectral Half Width	PCE (%) @ 25 ℃	PCE (%) @ 85 ℃	Hot/Cold Factor
Blue	459 nm	Direct	$Ga_{1-x}In_xN$	20 nm	66	63	0.95
Green	530 nm	Direct	$Ga_{1-x}In_xN$	30 nm	24	22	0.90
Amber	595-605 nm	Phosphor-Converted	$Ga_{1-x}In_xN$/Phosphor	80 nm	23	18	0.80
Amber	585-595 nm	Direct	$(Al_xGa_{1-x})_{0.5}In_{0.5}P$	20 nm	19	8	0.40
Red	615 nm	Direct	$(Al_xGa_{1-x})_{0.5}In_{0.5}P$	20 nm	44	24	0.55
Deep Red	650-670 nm	Direct	$(Al_xGa_{1-x})_{0.5}In_{0.5}P$	20 nm	49	39	0.80

Methodology: Power Conversion Efficiency (PCE) values at 25°C and hot/cold factors are reported for best-known commercially-available devices in each color range; PCE values at 85°C are computed from the PCE @ 25°C and hot/cold factors.





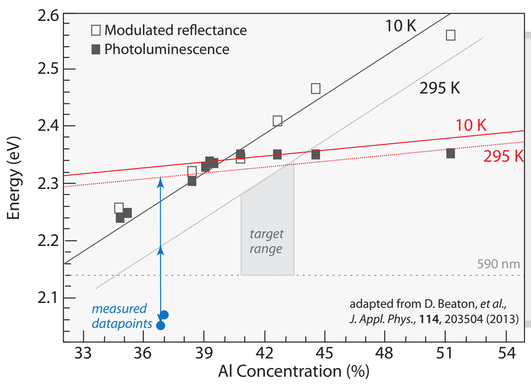


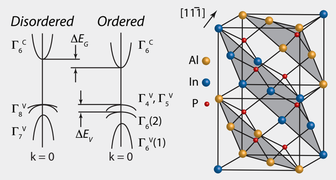
$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ LEDs suffer from internal intervalley transfer losses and external carrier leakage losses. These losses are fundamental to the $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ material system and can only be overcome by using another material.

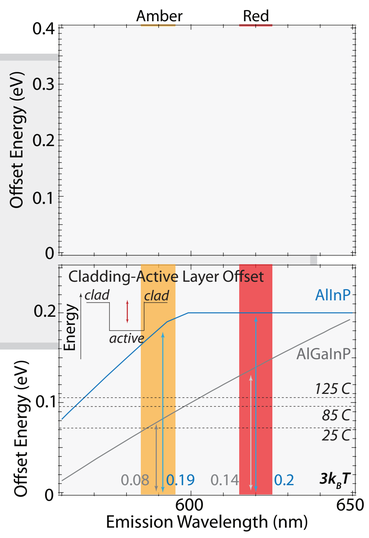
Direct bandgap $Al_xIn_{1-x}P$ has a higher direct-indirect bandgap energy crossover, which helps to reduce intervalley transfer. We combine $Al_xIn_{1-x}P$ with control of spontaneous atomic ordering to increase barriers to electron leakage to improve the efficiencies of red and amber LEDs.

$Al_xIn_{1-x}P$ Properties and Growth

Properties





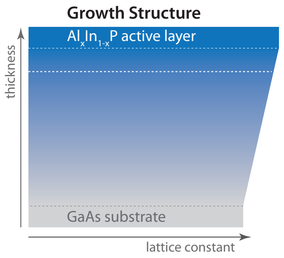


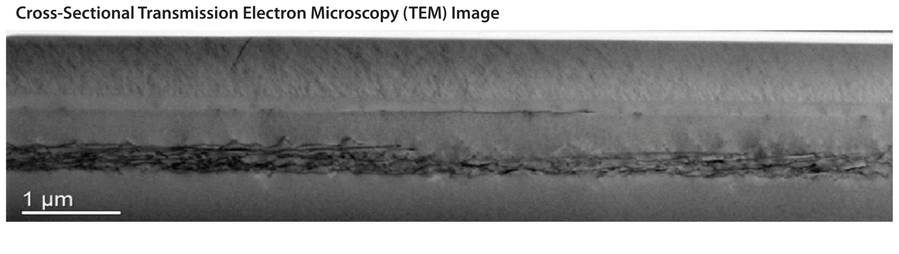
Al and In atoms can order along alternating [111] planes depending on the growth conditions. Ordering causes the bandgap to decrease via a reduction in the conduction band edge energy.

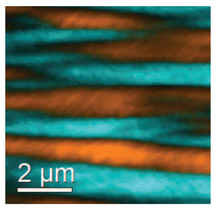
$Al_xIn_{1-x}P$ emits at 590 nm a compositions ~ 36-43% Al, depending on the ordering. We demonstrated $\Delta(\Gamma_{dis}\text{-}\Gamma_{ord})$ and $\Delta(X\text{-}\Gamma)$ offsets > 140 meV and are moving the composition toward the targeted range.

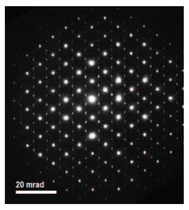
Given the offsets demonstrated here and in the literature, $Al_xIn_{1-x}P$ devices, the barriers to electron loss at amber emission wavelengths are expected to be similar to those in $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ red LEDs.

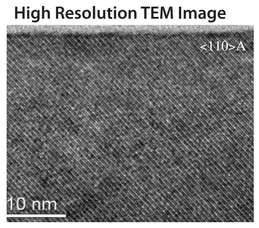
Metamorphic Growth

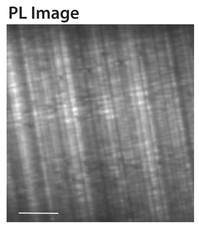








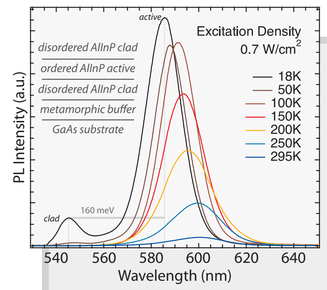


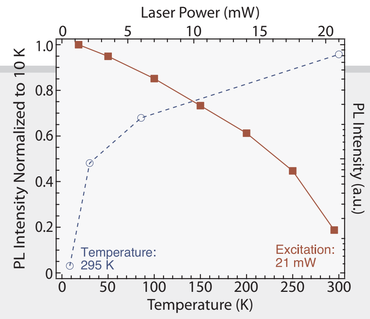


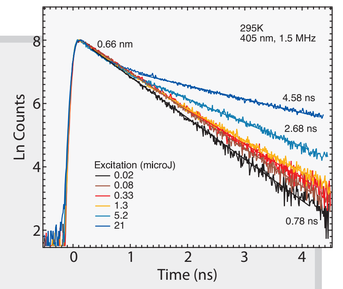
$Al_xIn_{1-x}P$ ($x < 0.43$) has a larger lattice constant than GaAs.

To prevent threading dislocations, a metamorphic buffer layer is used to extend the lattice constant before $Al_xIn_{1-x}P$ growth.

This approach reduces the dislocation density to 10^4 - 10^5 cm^{-2}.





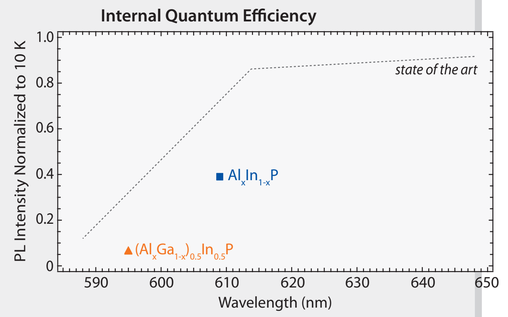


Photoluminescence (PL) measurements as a function of temperature and excitation density provide information about electron loss pathways.

PL from the cladding layer is observed at low temperatures, giving an indication of the energy barrier offset.

Time-resolved PL shows two characteristics decay times associated with radiative and non-radiative recombination that can be used to extract information about the internal quantum efficiency.

We initially used the ratio of PL intensity at 295 K/10K to estimate the internal quantum efficiency of simple $Al_xIn_{1-x}P$ double heterostructures and compared to $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ samples with similar structures. We are continuing to improve our $Al_xIn_{1-x}P$ material to increase luminescence.



Electroluminescence

Current-voltage measurements of double heterostructure devices indicate potential improvements in series resistance.

We are currently performing electroluminescence measurements as a function of temperature and drive current to determine how ordered/disordered $Al_xIn_{1-x}P$ LEDs differ from incumbent $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ devices in terms of emission efficiency.

Current and Potential Limiting Factors

1. Oxygen impurities

Deep traps associated with oxygen impurities increase non-radiative recombination. SIMS measurements indicate our devices have 10^{17} cm^{-3} oxygen impurities due to reactor-specific issues. While we cannot remedy the reactor design, we are looking into the use of higher V/III ratios to prevent oxygen inclusion.

2. Dislocations

We have limited the threading dislocations in our devices to 10^5 cm^{-2}. However, we find that the pattern of misfit dislocations within the buffer layer affects the luminescence. We are currently exploring whether this is due to strain, composition modulation or non-radiative recombination.

3. Ordered domains and composition modulation

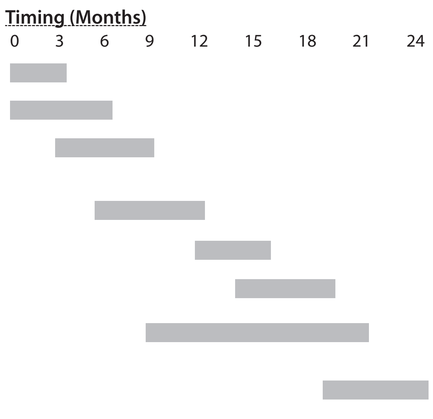
Domain boundaries between ordered variants and composition modulation on a short scale are observed. We do not yet know the extent to which domain boundaries or composition modulation impact non-radiative recombination.

4. Multiple quantum wells

The devices we have tested to-date mainly consist of double heterostructures without multiple quantum wells. We will begin to add in optimized MQW structures to improve radiative recombination.

Project Metrics and Milestones

Milestones and Progress Indicators



Maximize ordering in $Al_xIn_{1-x}P$ (λ = 590 nm) to be $\eta > 0.45$.

Demonstrate internal Γ-X offsets of 130 meV in ordered $Al_xIn_{1-x}P$ (λ = 590 nm).

Demonstrate electron confinement potentials of 130 meV in ordered/disordered $Al_xIn_{1-x}P$ heterostructures (λ =590 nm).

Demonstrate ordered $Al_xIn_{1-x}P$ (λ = 590 nm) with IQE = 75%.

Demonstrate $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ (λ = 590 nm) wtih IQE = 65%.

Impact analysis.

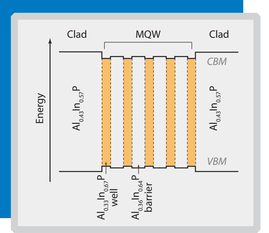
Demonstrate $Al_xIn_{1-x}P$ heterostructure LEDs (λ =590 nm) with a MQW active layer that exhibit higher EQE than equivalent $(Al_xGa_{1-x})_{0.5}1In_{0.49}P$ LEDs (λ = 590 nm).

Characterize loss channels in $Al_xIn_{1-x}P$ MQW structures. Evaluate the advantages and limitations of this approach.

Results Summary, Future Research and Considerations

We have shown that we can achieve large bandgap energy shifts with ordering. Our experiments suggest that we can achieve up to 200 meV direct/indirect and active/clad conduction band offsets, producing higher barriers to electron loss than incumbent $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ LEDs. We have also shown that we can metamorphically grow high quality $Al_xIn_{1-x}P$ heterostructures on GaAs substrates. Luminescence results indicate areas for improved performance by reducing non-radiative recombination sites and optimizing the device structure.

Going forward, we will continue to optimize the growth conditions to improve the $Al_xIn_{1-x}P$ material, incorporate multiple quantum well structures and analyze the potential of this approach to improve amber LED efficiency.



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